

# Search for Neutrinos from Dark Matter Annihilation in the Sun with the Baikal Neutrino Experiment

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**Abstract.** Upward through-going muons in the Lake Baikal Neutrino Experiment arriving from the ecliptic plane have been analyzed using NT200 data samples of the years 1998-2002 (1007 live days). We derive upper limits on muon fluxes from annihilation processes of hypothetical WIMP dark matter particles in the center of the Sun.

**Keywords:** Baikal, neutrino, solar WIMPs

## I. INTRODUCTION

Since long, galactic rotation curves indicate the existence of non-radiating dark matter. This evidence has been hardened also by evidences on larger cosmic scales, ending up with the largest scales, surveyed with the help of the cosmic microwave background radiation. In particular, the data suggest a dominant contribution of non-baryonic, non-relativistic (cold) dark matter. Among the favoured DM candidates are weakly interacting massive particles (WIMPs), in particular neutralinos as the lightest particles in many minimal supersymmetric models.

One strategy to search for a neutralino signal is to search for neutrinos produced in annihilation processes inside a large gravitational mass like the Sun. This method is well established since the nineties using underground and underwater(ice) neutrino telescopes. The Baikal Neutrino Experiment has published results of a search for neutrinos from WIMP annihilations in the core of the Earth [1], while the analysis with respect to the Sun is now presented the first time. We are looking for high energy neutrinos from the Sun in excess of the expected atmospheric neutrinos. The analysis is based on

data taken with the NT200 neutrino telescope between April 1998 and February 2003.

## II. THE BAIKAL NEUTRINO TELESCOPE

Located in Lake Baikal, South-East Siberia, the Neutrino Telescope NT200 is operated underwater at a depth of 1.1 km since 1998. The telescope detects Cherenkov light from upward and downward-going relativistic muons. NT200 consists of 192 optical modules (OMs) arranged pair-wise on 8 strings, with 12 pairs per string. The height of the detector is 72 m, its diameter is 42 m. Each OM contains a 37-cm photomultiplier tube (PMT). To suppress background from bioluminescence and dark noise, the two PMTs of a pair are switched in coincidence. Since 2005, the NT200 configuration was upgraded by additional 3 strings, each 100 m away from the center. This upgraded detector of about 10 Mton (named NT200+) serves as a prototype cell for a later Gigaton volume detector. The status of the Baikal Neutrino Telescope is presented at this conference [2].

## III. SELECTED DATA SAMPLES

We have analyzed NT200 data collected between April, 1998 and February, 2003, with a total of 1007 live days. Calibration methods and methods to reconstruct muon tracks have been described elsewhere [3], [4], [5]. Our analysis is based on data taken with the *muon trigger*. It requires  $N_{hit} \geq n$  within 500 ns, where *hit* refers to a pair of OMs coupled in a *channel*. Typically  $n$  is set to 3 or 4. The detector response to atmospheric neutrinos and muons has been obtained with Monte Carlo simulations based on standard codes like

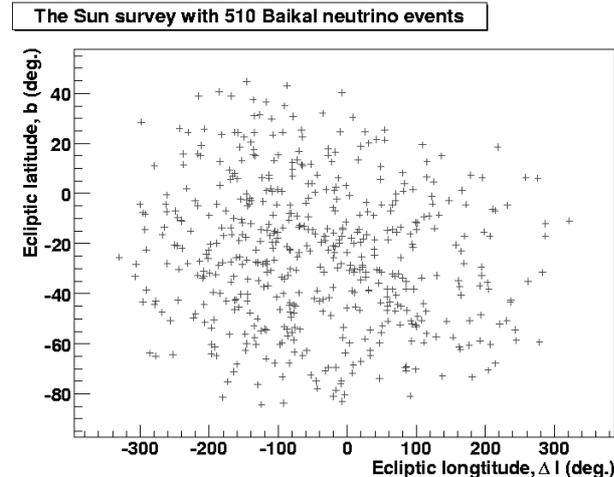


Fig. 1. Distribution of 510 upward muon directions in the ecliptic plane, with the Sun at the coordinate origin.

CORSIKA [6] and MUM [7], the Bartol atmospheric  $\nu$  flux [8] and the neutrino cross-sections from [9].

The offline filter which requires at least 6 hits on at least 3 strings ("6/3") selects about 40% of all triggered events. To distinguish upward and downward going muons on a one-per-million mis-assignment level, a filter with several levels of quality cuts was developed for the atmospheric neutrino ( $\nu_{at}$ ) analysis [10]. The atmospheric muons which have been misreconstructed as upward-going particles are the main source of background in a search for neutrino induced upward-going muons. To get the best possible estimator for the direction, we use multiple start guesses for the  $\chi^2$  minimization. For the final choice of the local minimum of  $\chi^2$  we use quality parameters which are not related to the time information. At the offline filter level ("6/3") the angular resolution ( $\Psi$  - r.m.s. mismatch angle) is about  $14.1^\circ$  for the  $\nu_{at}$ -sample. The present analysis defines two samples - sample A and sample B - which are optimized for the low and high WIMP-mass region, respectively. They use further differently tight quality cuts, resulting in different background contaminations and slightly different angular resolution. The quality cuts are applied to variables like the number of hit channels, the probability of fired channels to have been hit or not, the actual position of the track with respect to the detector centre and  $\chi^2/d.o.f.$ . To improve the signal-to-background ratio we used only events with reconstructed zenith angle  $\Theta > 100^\circ$ . This results in 2376 and 510 upward going muons for sample A and B, respectively (with  $\nu_{at}$ -angular resolutions  $\Psi = 5.3^\circ$  and  $\Psi = 3.9^\circ$ ). Both  $\Psi$  values are much bigger than the visible size of the Sun. However the angular window for a signal search may be even larger, since at least at energies below 100 GeV the kinematical angle between neutrino and muon dominates.

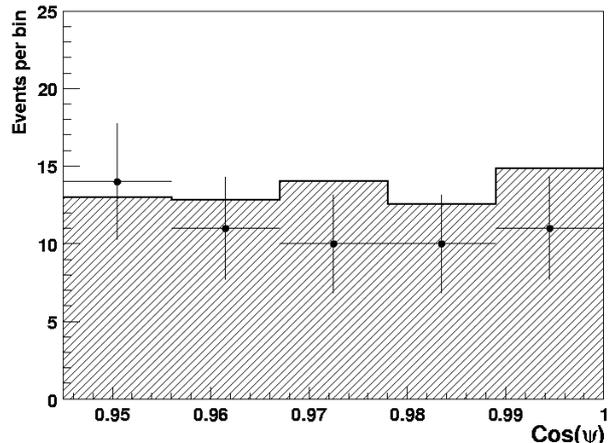


Fig. 2. Distribution of correlation angles between muons and the Sun for data sample A of 2376 events: data (bullets) and measured background (histogram).

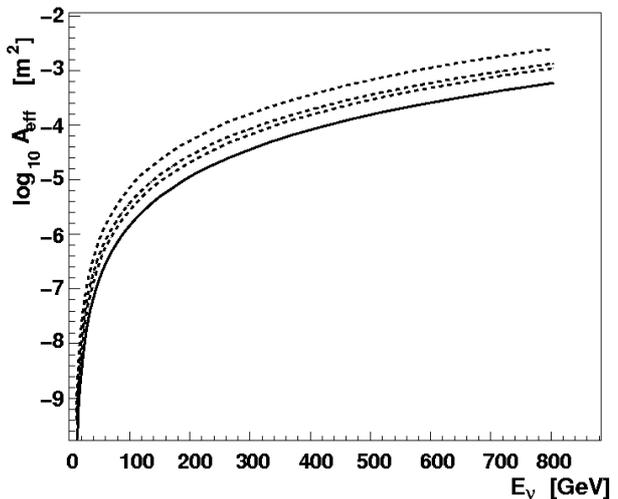


Fig. 3. Neutrino effective area of NT200 versus neutrino energy for different selection cuts. Curves from top: offline filter level without (short dashed) and with correction (long dashed) for the Sun track; for event sample B without (dots) and with correction (solid line) for the Sun track.

#### IV. SKY-PLOT ANALYSIS

A map of the ecliptic plane centered at the Sun is shown in Fig.1 with 510 upward going muons. No clustering toward the Sun is observed. The distribution of the correlation angles between muons and the Sun is shown in Fig.2. The dots refer to angles with the real position of the Sun, the histogram to angles with "fake Suns", defining the expected background behaviour.

No excess is observed, resulting in upper limits on number of muons from the Sun. Table I gives the upper limits at 90% confidence level (c.l.) for the two selected data samples. We give numbers for three values of the half cone to the Sun which are used in the dark matter analysis. To obtain upper limits on the muon numbers we used the recipes for low statistics given in the PDG [11] and well as the Feldman-Cousins method [12] (numbers

for FC in parentheses).

#### V. UPPER LIMITS ON A DARK MATTER SIGNAL FROM THE SUN

To derive limits on neutrino and muon fluxes one needs the effective area of the detector. Fig.3 shows the NT200 area for neutrinos as a function of neutrino energy. The expected numbers of muons generated by neutrinos is obtained from the neutrino flux  $\Phi^\nu$  of the considered source and the effective area  $A_{eff}^\nu$  of the neutrino telescope:

$$N_\mu = \int_{E_{th}}^{E_{up}} A_{eff}^\nu(E_{th}, E_\nu, \Theta, \phi) \times \frac{d^2\Phi^\nu}{dE_\nu d\Omega} dE_\nu d\Omega \quad (1)$$

For neutrinos originating from WIMP annihilation, the maximum energy  $E_{up}$  is equal to the WIMP mass  $m_{WIMP}$ , with theory suggesting WIMP masses in the GeV-TeV range. With increasing  $m_{WIMP}$  more and more channels open up – both in annihilation and decay processes. The contribution of energetic (“hard”) neutrinos can significantly increase when the WIMP mass becomes larger than the respective energy threshold for the production of heavy secondaries.

From calculations of the expected number of muons  $N_\mu$  according to (1), with the DM neutrino spectra from [13], we estimated the size of the angular bin for which a WIMP signal could be detected with 90% probability. The found relation between half open cone toward the Sun and WIMP mass is shown in Fig.4. The three angular bins in Table I are those for 90% probability of signal detection ( $M \geq 90$  GeV,  $M=50$  GeV and  $M=30$  GeV, respectively). Further the upper limits on muon numbers were scaled to WIMP masses. Table I gives the number of events (data, expected background and 90% c.l. upper limit). We assumed neutrinos to be produced in two annihilation channels, b anti-b (soft channel) and  $W^+W^-$  (hard channel) which define the respective maximum energy  $E_{up}$  for neutrinos. The resulting upper limits on muon fluxes at 90% c.l. are shown in Fig.5, as function of the WIMP mass, for the two selected samples and for soft and hard neutrino spectra (normalized to  $E_{thr}=1$  GeV). The upper limit on the WIMP-induced neutrino flux from the Sun is found to be  $F_\nu = 4.46 \times 10^{10} km^{-2} \times yr^{-1}$  for  $m_{WIMP} = 100 GeV/c^2$  and for the annihilation channel  $W^-W^+$  (sample B).

#### VI. DISCUSSION

Up to now all operating neutrino telescopes (see the talks of the IceCube and ANTARES collaborations at this conference) and the past generation (Baksan [13],[14] MACRO [15], Super-Kamiokande [16]) reported no excess of upward going muons from the direction of the Sun when compared to the expectation for atmospheric neutrinos. This constrains both the annihilation rate in the Sun and (in concert with direct WIMP searches) the WIMP interaction cross section.

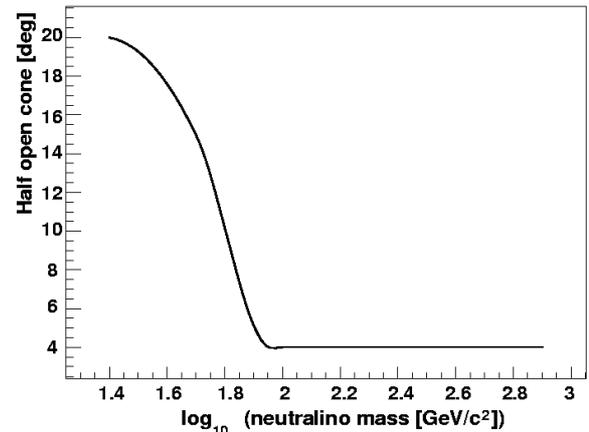


Fig. 4. Half cones for muon direction toward the Sun where the signal from a WIMP of a given mass could be detected with 90% probability.

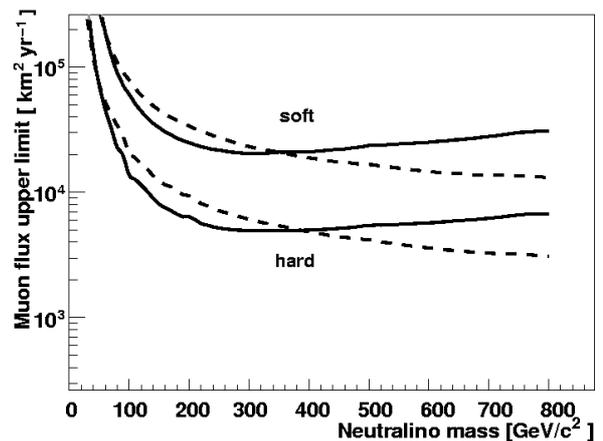


Fig. 5. The Lake Baikal NT200 upper limits at 90% c.l. on the muon flux from the Sun for a given WIMP mass (sample A - dashed line, sample B - solid line); “hard” neutrino fluxes are the lower two lines, “soft” the upper two lines.

Upper limits on muon fluxes from the Sun obtained by neutrino telescopes are shown in Fig.6 (adapted from [17]; all limits are for 1 GeV threshold). The Baikal curve corresponds to hard neutrino spectra and is for  $m_{WIMP} < 370 GeV/c^2$  obtained from sample B, above this value from sample A (extrapolated up to 3 TeV). The AMANDA-II [17] and IceCube [18] limits are shown for hard neutrino spectra.

The presented results are preliminary, and allow to estimate the NT200 sensitivity for high energy neutrinos from DM annihilation processes in the Sun.

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TABLE I  
THE 90% C.L. UPPER LIMITS ON THE NUMBER OF MUON EVENTS FROM THE SUN FOR ANALYSIS SAMPLES A AND B, CALCULATED ACCORDING TO PDG AND (IN BRACKETS) FC, RESPECTIVELY.

Half-cone	Sample B			Sample A		
( $\circ$ )	$N_{obs}$	$N_{bkg}$	$N_{c.l.}$	$N_{obs}$	$N_{bkg}$	$N_{c.l.}$
4	1	1.5	3.1 (2.9)	5	5.8	4.8 (4.2)
15	4	8.0	3.6 (2.0)	36	47.3	7.10
20	11	16.3	4.9 (2.9)	78	87.7	11.50

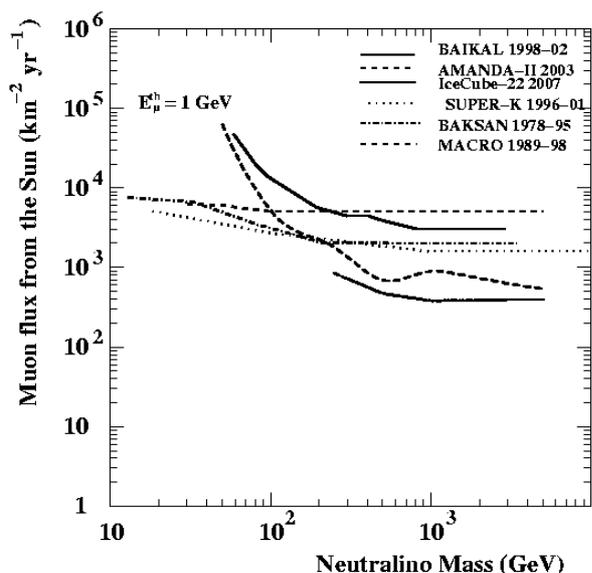


Fig. 6. Upper limits at 90% c.l. on the muon flux from the Sun versus WIMP mass: Baikal NT200, MACRO [15], Baksan [13], Super-Kamiokande [16], AMANDA-II [17] and IceCube 22-strings [18].

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